A UV description of a Composite Higgs

Tony Gherghetta
University of Minnesota

Lattice for Beyond the Standard Model Physics,
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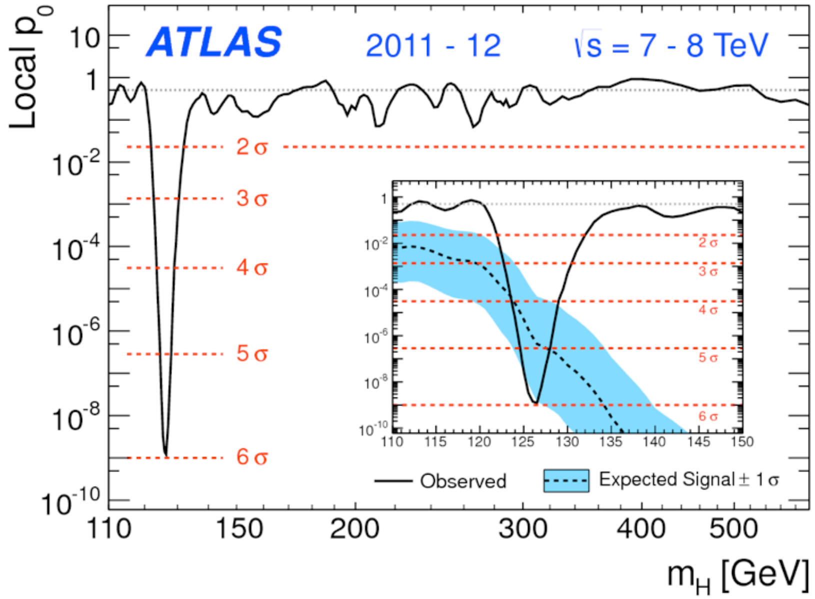
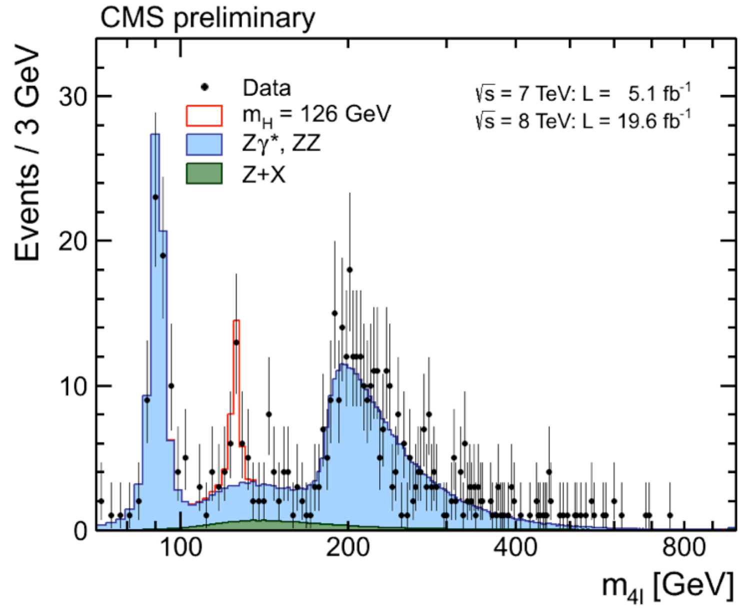
[James Barnard, TG, Tirtha Sankar Ray, arXiv:1311.6562]

Higgs discovery - LHC Run I



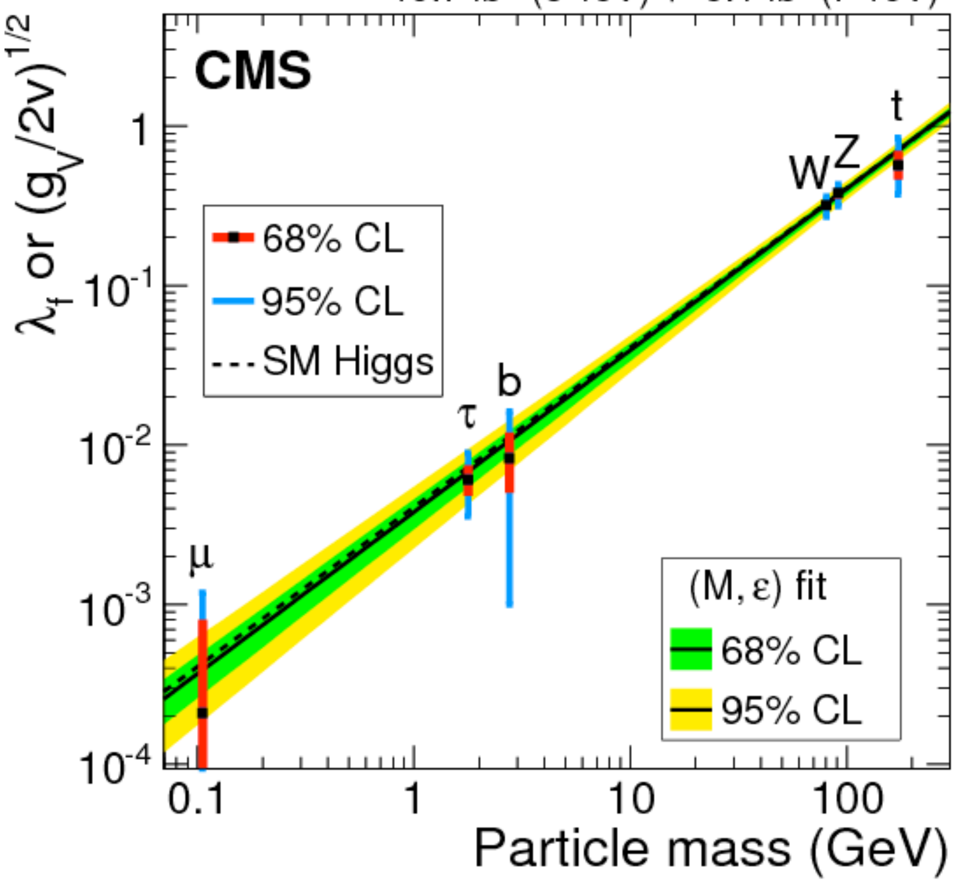


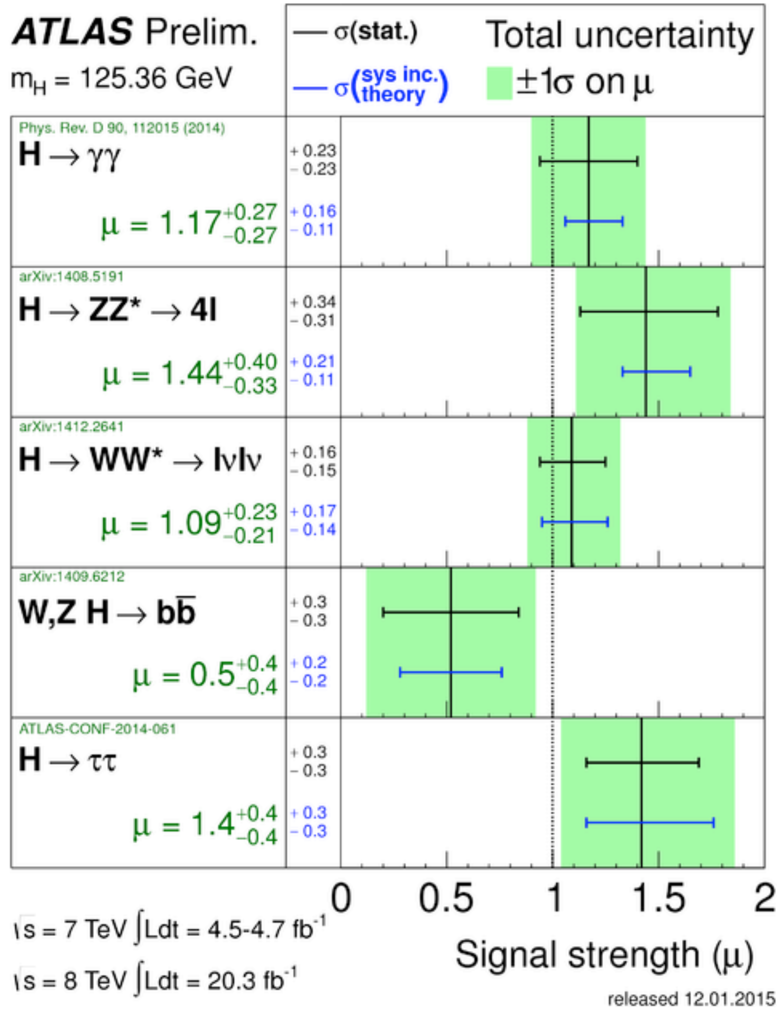
Higgs potential: $V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4$ $\qquad \langle H \rangle = \frac{1}{\sqrt{2}}(v+h)$

$$v^2 = \frac{\mu_h^2}{\lambda_h} \simeq (246 \text{ GeV})^2 \qquad m_h^2 = 2\lambda_h v^2 \simeq (125 \text{ GeV})^2$$

$$\Rightarrow \quad \boxed{\mu_h^2 \simeq (89 \text{ GeV})^2} \qquad \boxed{\lambda_h \simeq 0.13}$$

Higgs couplings





Looks very much like a SM Higgs boson!

What is the nature of the Higgs boson?

HIGGS BOSON

- Elementary? ⇒ Standard Model/ Supersymmetry

OR

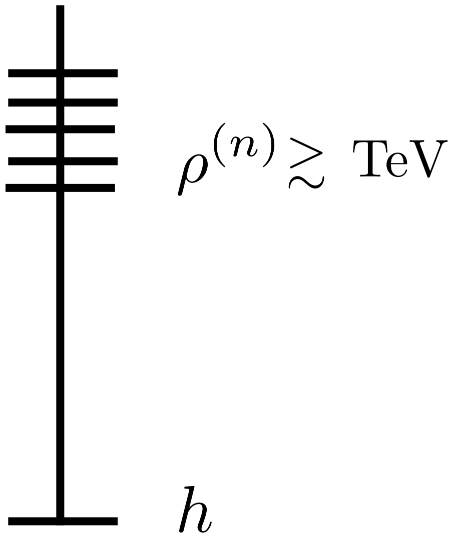
- Composite? ⇒ New strong dynamics

How to obtain a mass ~125 GeV much below the Planck scale?

Composite Higgs

Higgs as a pseudo Nambu-Goldstone boson [Georgi, Kaplan `84]

Global symmetry G spontaneously broken to subgroup H at scale f



Resonance mass: $m_\rho \sim g_\rho f \qquad 1 \lesssim g_\rho \lesssim 4\pi$

coset $G/H \supset h$

Higgs mass protected by shift symmetry
-- like pions in QCD

BUT global symmetry must be explicitly broken to generate $V(h) \neq 0$

Global symmetry broken by mixing with elementary sector

[Contino, Nomura, Pomarol `03; Agashe, Contino, Pomarol `04]

SM matter and gauge fields

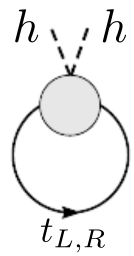
Ψ_i, A_μ

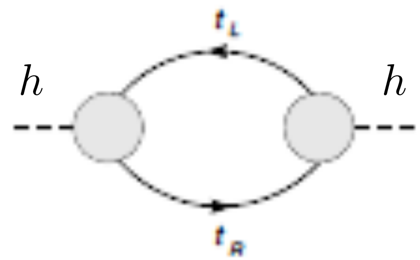
$\mathcal{L}_{mix} = \lambda_{L,R} \bar{\Psi}_{L,R} \mathcal{O}_\Psi + g_V A^\mu J_\mu$

strongly-coupled Higgs sector

$\mathcal{O}_i$

Higgs potential





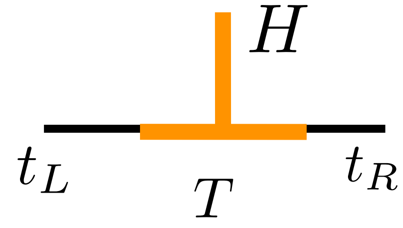
$V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4$ where $\mu_h^2 \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 f^2$ $\lambda_h \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2$

EWSB $\left(\langle H \rangle = \frac{v}{\sqrt{2}}\right)$ $v^2 = \frac{\mu_h^2}{\lambda_h}$ $\Rightarrow$ **Tuning:** $\Delta^{-1} \sim \frac{v^2}{f^2} \lesssim 10\%$

$(v = 246 \text{ GeV}, f \gtrsim 750 \text{ GeV})$

Higgs mass:

$$m_h^2 \simeq \frac{N_c}{\pi^2} m_t^2 \frac{m_T^2}{f^2} \quad = g_T^2$$



$m_T =$ fermion resonances (EM charges $5/3, 2/3, -1/3$)

$$m_T \sim m_\rho \gtrsim 2.5\,\text{TeV} \quad (g_T \sim g_\rho \gtrsim 3) \quad \Rightarrow \quad m_h \gtrsim m_t$$

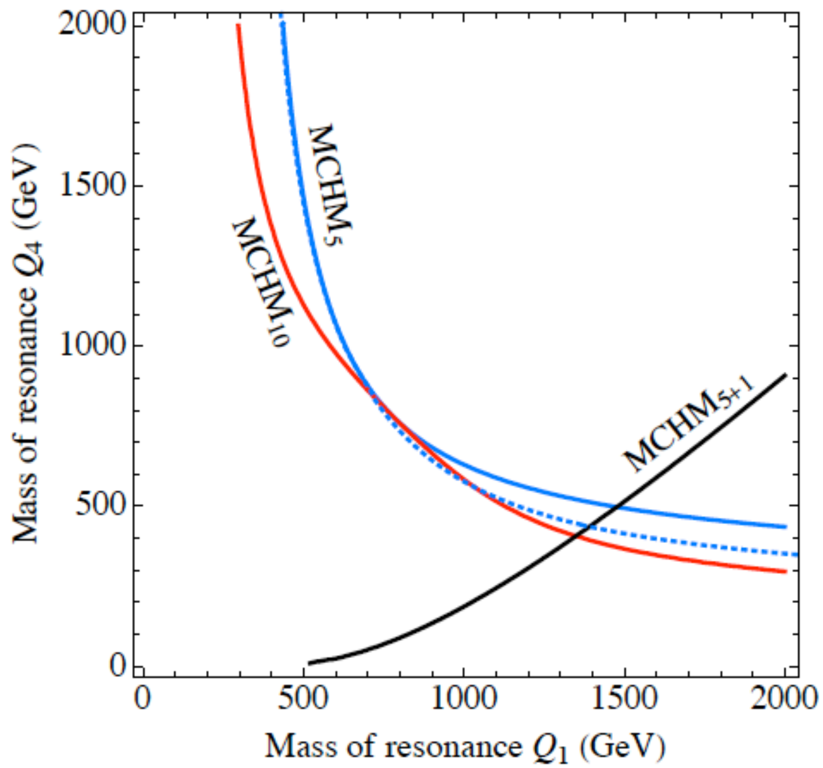
But, no need for $m_T \sim m_\rho$

$m_h \sim 125$ GeV

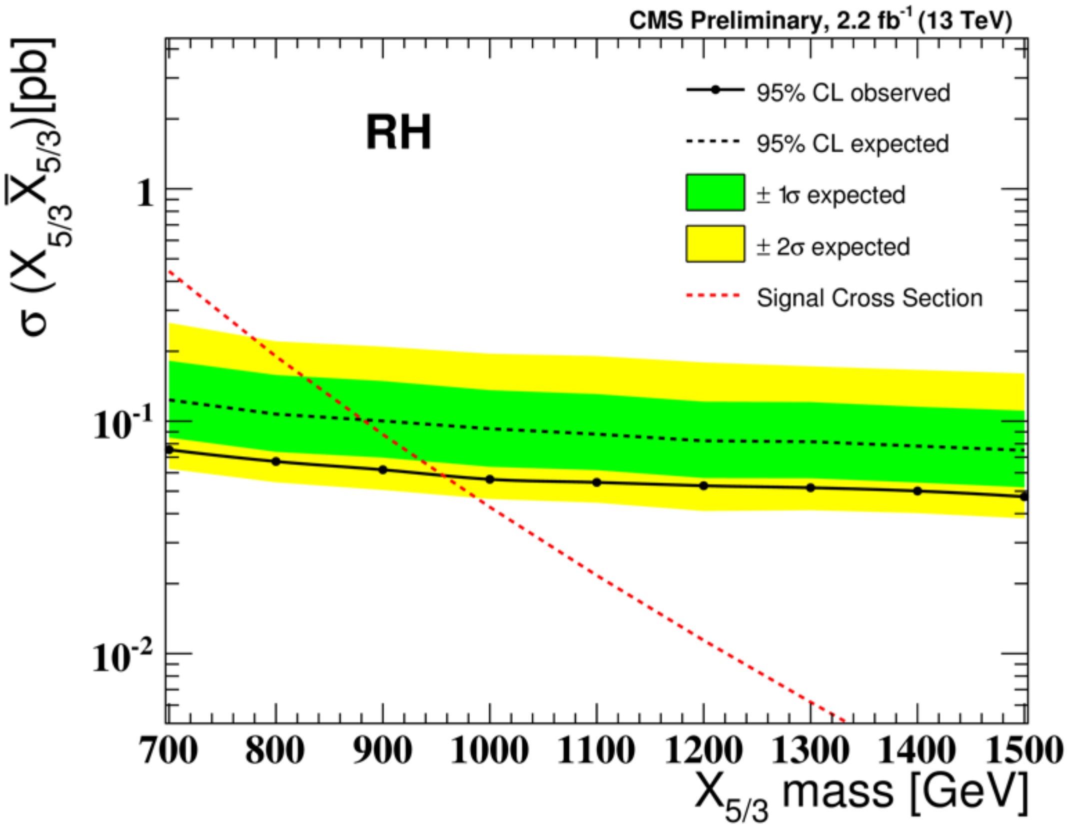
$\Rightarrow \quad m_T < m_\rho$

light fermion resonances!

[Marzocca, Serone, Shu 2012; Pomarol, Riva 2012]



LHC Limits: *The Missing Resonances Problem*



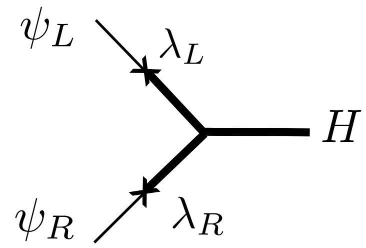
$$\Rightarrow \quad m_T \gtrsim 940 - 960 \text{ GeV}$$

Partial compositeness:

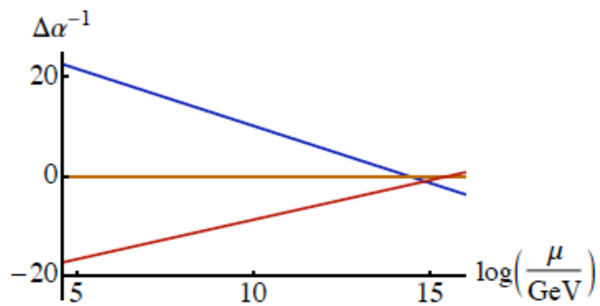
$$\boxed{\mathcal{L} = \lambda_L \psi_L \mathcal{O}_R + \lambda_R \psi_R \mathcal{O}_L}$$

Explains the fermion mass hierarchy [Kaplan 91; TG, Pomarol 00]

$$m_f \sim \lambda_L \lambda_R v \quad \text{where} \quad \lambda_{L,R} \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{\dim\, \mathcal{O}_{L,R} - \frac{5}{2}}$$



Composite (RH) top quark



GAUGE COUPLING UNIFICATION

[Agashe, Contino, Sundrum '05]

Features of Composite Higgs models:

- Higgs is pseudo Nambu-Goldstone boson

$G \to H$ at scale f where $H \supset SO(4) \sim SU(2)_L \times SU(2)_R$

- Partially composite top $\boxed{\mathcal{L} = \lambda_L t_L \mathcal{O}_R + \lambda_R t_R \mathcal{O}_L}$

$m_t \sim \lambda_L \lambda_R v$ where $\lambda_{L,R} \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{\dim\, \mathcal{O}_{L,R} - \frac{5}{2}}$ $\Rightarrow$ $\dim\, \mathcal{O}_{L,R} \sim \frac{5}{2}$

What is the UV description responsible for these features?

- AdS/CFT -- D-brane engineering
- Supersymmetric (e.g. Seiberg duality)

[Caracciolo, Parolini, Serone 1211.7290]

} Involves scalars

Look for one without elementary scalars...

Candidate: SO(6)/SO(5) model

[Gripaios, Riva, Pomarol, Serra `09]

[Other possibilities classified by Ferretti, Karateev 1312.5330]

$$SO(6)/SO(5) \sim SU(4)/Sp(4)$$
$$= \underbrace{\mathbf{2}}_{\text{Higgs doublet}} \text{ of } SU(2)_L + \mathbf{1} \text{ singlet}$$

Symmetry breaking-pattern $\quad SU(4) \xrightarrow{f} Sp(4)$

What is the dynamics that realizes this?

Introduce new strong gauge group $Sp(2N_c)$
with 4 Weyl fermion flavors ψ^a $(a = 1, \ldots, 4)$

➡ $SU(4)$ global symmetry

Gauge-invariant fermion bilinear: $\Omega_{ij}\psi^a_i\psi^b_j = \mathbf{6}$ of $\mathrm{SU}(4)$

$Sp(2N_c)$ is asymptotically free $b = \frac{11}{3}(2N_c+2) - \frac{2}{3}\times 4 = \frac{2}{3}(11N_c+7) > 0$

and confines ➡ $SU(4) \to Sp(4)$

Under what conditions does this happen?

SU(4) gauged NJL model

$$\mathcal{L}_{\rm int} = \frac{\kappa_A}{2N_c}(\psi^a\psi^b)(\bar{\psi}_a\bar{\psi}_b) + \frac{\kappa_B}{8N_c}\left[\epsilon_{abcd}(\psi^a\psi^b)(\psi^c\psi^d) + {\rm h.c.}\right]$$

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(4)$
ψ	$\square$	$\mathbf{4}$
M	$\mathbf{1}$	$\mathbf{6}$

Can be rewritten as

$$\begin{aligned}\mathcal{L}_{\rm int} = &-\frac{1}{\kappa_A+\kappa_B}\left[\left(\kappa_A M^*_{ab} + \frac{1}{2}\kappa_B\epsilon_{abcd}M^{cd}\right)(\psi^a\psi^b) + {\rm h.c.}\right] \\ &- \frac{2N_c\kappa_A}{(\kappa_A+\kappa_B)^2}M^{ab}M^*_{ab} - \frac{N_c\kappa_B}{2(\kappa_A+\kappa_B)^2}\left(\epsilon_{abcd}M^{ab}M^{cd} + {\rm h.c.}\right)\end{aligned}$$

Like "massive Yukawa theory"

where $M^{ab} = -\frac{\kappa_A+\kappa_B}{2N_c}(\psi^a\psi^b)$ "auxiliary scalar field"

One-loop effective potential

$$V(m) = \frac{N_c\kappa_A}{\kappa_A^2-\kappa_B^2}(\bar{m}_1^2+\bar{m}_2^2) - \left|\frac{2N_c\kappa_B}{\kappa_A^2-\kappa_B^2}\right|\bar{m}_1\bar{m}_2$$
$$-\frac{N_c}{8\pi^2}\sum_{i=1}^{2}\left[\Lambda^2\bar{m}_i^2 + \bar{m}_i^4\ln\left(\frac{\bar{m}_i^2}{\Lambda^2+\bar{m}_i^2}\right) + \Lambda^4\ln\left(\frac{\Lambda^2+\bar{m}_i^2}{\Lambda^2}\right)\right]$$

Λ = UV cutoff scale

where

$$M = \begin{pmatrix} 0 & m_1 & 0 & 0 \\ -m_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_2 \\ 0 & 0 & -m_2 & 0 \end{pmatrix}$$

$$|\bar{m}_1|^2 = \frac{4|\kappa_A m_1^* + \kappa_B m_2|^2}{(\kappa_A+\kappa_B)^2} \qquad |\bar{m}_2|^2 = \frac{4|\kappa_A m_2^* + \kappa_B m_1|^2}{(\kappa_A+\kappa_B)^2}$$

Minimum condition

$$\boxed{1 - \frac{\bar{m}^2}{\Lambda^2}\ln\left(\frac{\Lambda^2+\bar{m}^2}{\bar{m}^2}\right) = \frac{4\pi^2}{\Lambda^2}\left(\frac{\kappa_A}{\kappa_A^2-\kappa_B^2} - \left|\frac{\kappa_B}{\kappa_A^2-\kappa_B^2}\right|\right) \equiv \frac{1}{\xi}}$$

Solutions

$$\begin{cases} m_1 = m_2 = 0 & 0<\xi<1 & SU(4) \text{ unbroken} \\ m_1 = m_2 = \dfrac{\bar{m}}{2} & \xi > 1 & SU(4) \to Sp(4) \end{cases}$$

⇨ $\xi = 1$ is a critical point

Treat Λ as a renormalization scale: $\beta(\xi) = \Lambda \frac{\partial \xi}{\partial \Lambda} \approx 2\xi(1-\xi)$

⇨ UV fixed point at $\xi = 1$ $(\Lambda \to \infty \text{ with } \bar{m} \text{ finite})$

Dynamically generated fermion mass $\bar{m} = -\frac{4\pi^2 \xi}{N_c \Lambda^2} \langle \psi\psi \rangle$

Near $\xi \approx 1$ $\bar{m}(\Lambda) = \left(\frac{\mu_0}{\Lambda}\right)^2 \bar{m}(\mu_0) \equiv Z_m \bar{m}(\mu_0)$ $\mu_0 =$ reference scale

Large anomalous dimension $\gamma_m \equiv -\frac{\Lambda}{Z_m} \frac{\partial Z_m}{\partial \Lambda} = 2$ [Miransky, Yamawaki `89; Kondo, Tanabashi, Yamawaki `92]

$$\dim \psi\psi = 3 - \gamma_m = 1$$

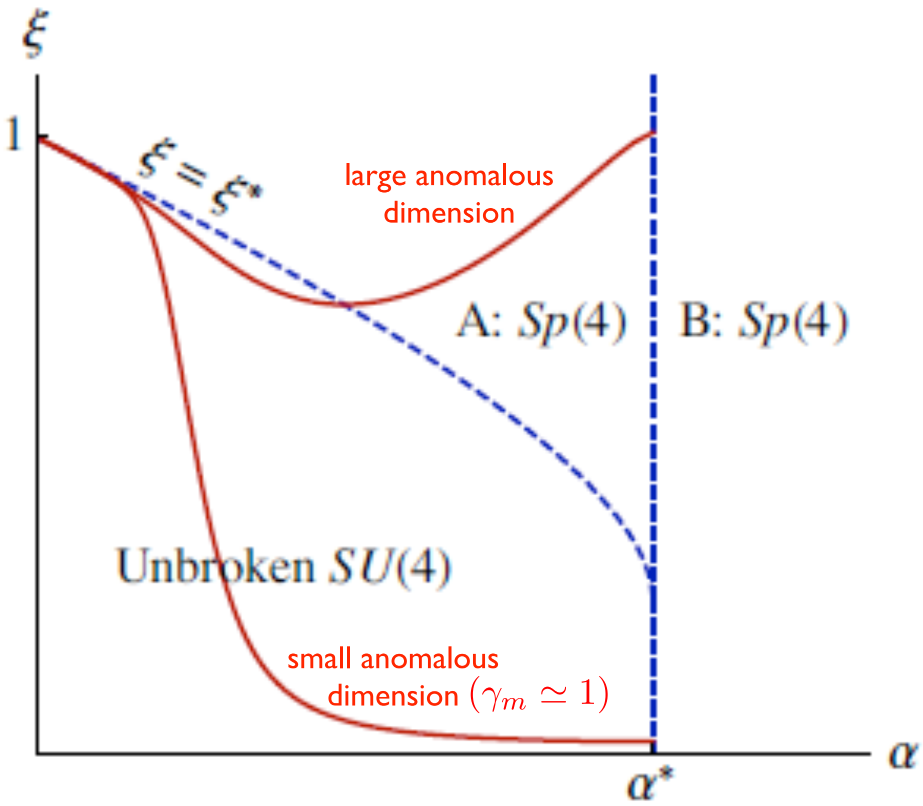
⇨ Four-fermion operator has dimension 2

-- model appears to be renormalisable in the UV!

Need to include gauge interaction and solve Schwinger-Dyson equation

[Bardeen, Leung, Love `86] [Appelquist, Soldate, Takeuchi, Wijewardhana`88; Kondo, Mino, Yamawaki `89]

For Sp(2Nc) gauge group obtain [Barnard, TG, Sankar Ray 1311.6562]



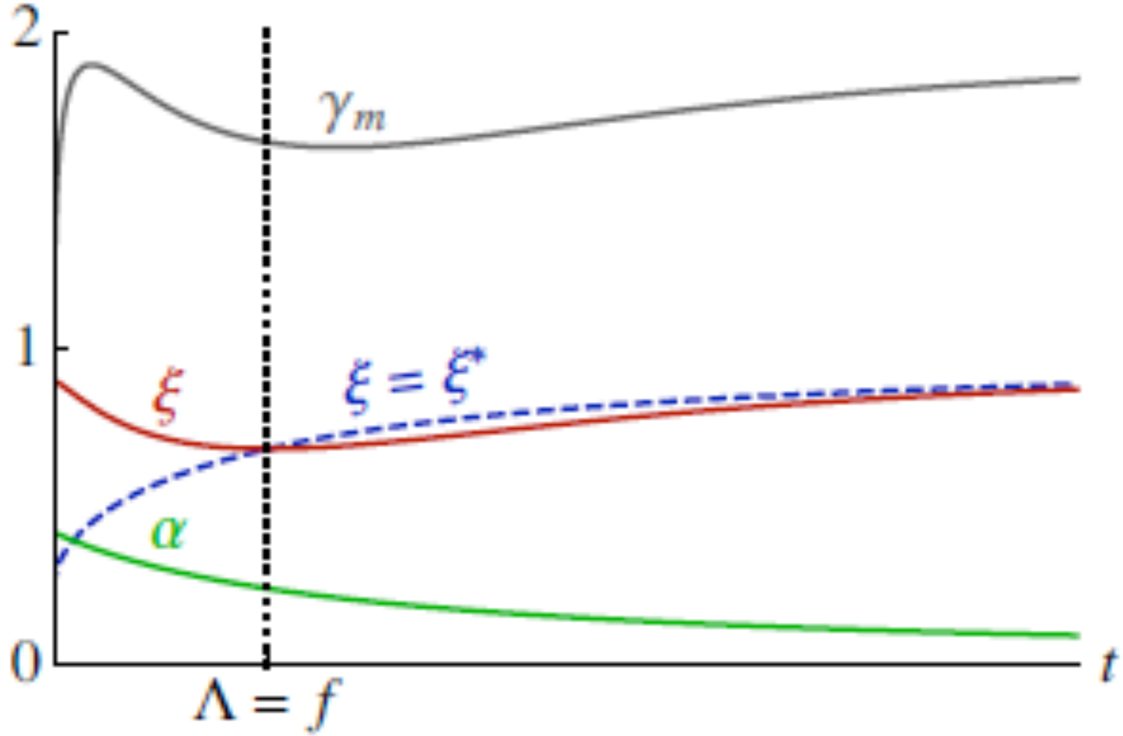
Large anomalous dimension for

$\xi \approx \xi^*$ and $\alpha \ll \alpha^*$

$$\boxed{\gamma_m \simeq 2 - \frac{\alpha}{2\alpha^*}}$$

Evolution of couplings: (for upper trajectory)

[Barnard, TG, Sankar Ray 1311.6562]



*Spontaneous breaking of global symmetry driven **mainly** by 4-fermion interaction!*

Top partners

Introduce a pair of colored vector-like fermions $\chi, \tilde{\chi}$

transform as two-index antisymmetric representation of Sp(2Nc)

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(4)$	$\mathrm{SU}(3)_c \times \mathrm{U}(1)$
ψ	$\square$	$\mathbf{4}$	$\mathbf{1}_0$
χ	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{3}_{+2/3}$
$\tilde{\chi}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\bar{\mathbf{3}}_{-2/3}$

Gauge-invariant combinations: $(\psi^a\chi^f\psi^b) = \psi^a_i\Omega_{ij}\chi^f_{jk}\Omega_{kl}\psi^b_l$ etc.

$$\Psi_1{}^{abf} = (\psi^a\chi^f\psi^b) \qquad \Psi_2{}^f_{ab} = (\bar{\psi}_a\chi^f\bar{\psi}_b) \qquad \Phi^b_{af} = (\bar{\psi}_a\bar{\chi}_f\psi^b)$$

$$\tilde{\Psi}_1{}^{abf} = (\psi^a\tilde{\chi}_f\psi^b) \qquad \tilde{\Psi}_2{}^f_{ab} = (\bar{\psi}_a\tilde{\chi}_f\bar{\psi}_b) \qquad \tilde{\Phi}^b_{af} = (\bar{\psi}_a\bar{\tilde{\chi}}^f\psi^b)$$

transform as

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(4)$	$\mathrm{SU}(3)_c \times \mathrm{U}(1)$
$\Psi_{1,2}$	$\mathbf{1}$	$\mathbf{6}$	$\mathbf{3}_{+2/3}$
Φ	$\mathbf{1}$	$\mathbf{15} \oplus \mathbf{1}$	$\bar{\mathbf{3}}_{-2/3}$
$\tilde{\Psi}_{1,2}$	$\mathbf{1}$	$\mathbf{6}$	$\bar{\mathbf{3}}_{-2/3}$
$\tilde{\Phi}$	$\mathbf{1}$	$\mathbf{15} \oplus \mathbf{1}$	$\mathbf{3}_{+2/3}$

top partner candidates

Recall: $\mathcal{L} = \lambda_L t_L \mathcal{O}_R + \lambda_R t_R \mathcal{O}_L$

UV description: $\mathcal{O}_{L,R} \leftrightarrow \underbrace{\psi\chi\psi}$

(Diquark approximation to baryons [Ball `90])

= tightly bound $\psi\psi$ by 4-fermion interaction, bound to χ by Sp(2Nc) gauge interaction $(\xi \gg \sqrt{\alpha})$

$$\dim \mathcal{O}_{L,R} = \dim \psi\chi\psi \approx \underbrace{\dim \psi\psi}_{3-\gamma_m} + \frac{3}{2} = \frac{5}{2} + \frac{\alpha}{2\alpha^*}$$

Marginally irrelevant!

➡ Allows for order-one top Yukawa coupling!

$\xi \gg \sqrt{\alpha}$

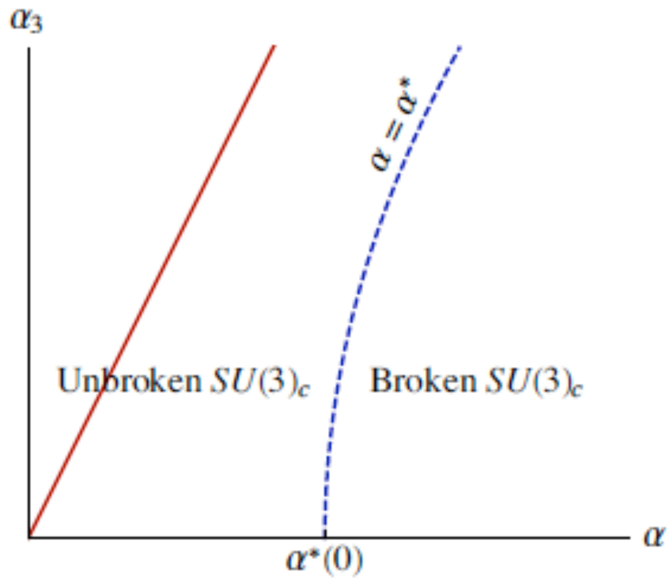
➡ Top partners are naturally lighter than uncolored partners!

In addition there are ***scalar*** bound states:

	$Sp(2N_c)$	$SU(4)$	$SU(3)_c \times U(1)$
M	$\mathbf{1}$	$\mathbf{6}$	$\mathbf{1}_0$
S	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}_0$
R	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{8}_0$
P	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{6}_{+4/3}$
$\tilde{P}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{6}}_{-4/3}$

Coloured bound states cannot get a VEV

Coloured scalars must be stabilised by the SU(3) gauge interactions.



Require: $$\frac{\alpha}{\alpha_3} < \frac{d\alpha^*}{d\alpha_3}$$

Conclusion

- The Higgs boson could be composite

  --- Higgs is a pseudo Nambu-Goldstone boson

  --- Partially composite top sector

- SO(6)/SO(5) model has a simple UV description

  --- Only fermions and gauge bosons, *no elementary scalars!*

  --- Large anomalous dimension implies four-fermion interaction is renormalisable

- This simple framework can be applied to other coset groups